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FINAL REPORT

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"Trapped Particle Absorption by the Ring of Jupiter"

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Introduction

Our main purpose in this grant is to study the interaction of trapped radiation with the ring of Jupiter. Because it is an identical problem, we are interested in the rings of Saturn and Uranus as well. At Jupiter and Saturn we have data from the Pioneer 11 encounter, for which we are able to deduce some of the properties of the rings themselves. We have also looked into our Pioneer encounter data sets for some additional effects suggested to us as worthwhile by colleagues.

Progress

We have purchased and installed 160 Mbytes of special purpose disc storage for our VAX computer system. This storage capacity will be used to hold several data sets for analyzing and merging our ring interaction data with others. We have over a dozen tapes in this space at present, but, since it was installed only recently, we have not yet finished the software we will use to access it all. Soon we will have the magnetometer output directly at our fingertips, and this will help us to interpret the angular distribution changes we see in the energetic particles throughout the ring interaction regions.

We have over a dozen Jupiter magnetic field models available in a program that integrates the adiabatic invariants to compute B and L. We have used this program to label our UCSD Pioneer 11 encounter data with the most satisfactory of these models and have written the output onto magnetic tape and disc for convenient reference. When our routines for accessing the magnetic field data become available, these will be the data sets that we will use for further analysis.

We have studied the expected effects of absorbing material on the trapped radiation to obtain the loss rate as a function of ring properties. For the case of azimuthal symmetry and random probability of impact, analytical expressions can be obtained for all sizes of absorbers and all particle gyroradii and pitch angles (although nobody has published them to date.) With the results of a particle diffusion analysis, one then has an inverse problem to deduce the poperties of the ring, given the loss rate. Our purpose is to combine these loss functions with the diffusion analysis.

Analysis of the particle diffusion problem rounds out the theoretical end of the ring absorption problem. We have used two approaches, one quick and dirty and hard to justify, and the other slow, dirty, and easy to justify. We have made progress with the latter, and are ready to try it now on our data. We want to develop both approaches in a way that illuminates the relationship between their results. We wrote a paper using the first approach [Fillius, W., M. F. Thomsen, J. A. Van Allen, W.-H. Ip, M. Acuna, and N. F. Ness, "Trapped Radiation Absorption at the Ring of Jupiter"], but held up publication because of the critical nature of the results. We want to do a more thorough analysis before we announce our conclusions. The paper is appended to this report.

Other projects which have arisen include identification of decay products for energetic particle albedo off the rings and moons of Saturn

a search for flux transfer events at the Jovian magnetopause. The first of these is a joint effort with Ted Northrop at GSFC, Bernie Blake at Aerospace Corporation, and Steve Margolis at St. Louis University. Blake and Margolis have proposed that very energetic electrons must be produced by energetic particle interactions with Saturn's moons, and particularly Mimas, Janus, and Epimetheus. These latter are particularly suited to an experimental search, since the particles' mobility is low enough this close in for them to accumulate to detectable intensities. At the time of the Pioneer 11 encounter, we tried and failed to account entirely for certain anomalies in one of our counter channels that we knew was responding at least partially to very high energy protons. Now it seems likely that these anomalies were caused by the Blake-Margolis electrons. Northrop has worked out a very elegant theory which relates the angular distributions to the flux gradients of large gyroradius particles, and this is just what we need to separate the protons from the electrons. Thus we anticipate that this project will establish the existence of a previously unidentified component of the Saturnian radiation belt. Also we anticipate a new point on the high energy proton spectrum, which will be important to the cosmic ray albedo theory of the origin of these particles. [See Fillius, W., and C. McIlwain, "Very Energetic Protons in Saturn's Radiation Belt," J. Geophys. Res., 85, 5803-5811, Nov. 1, 1980.] Needless to say, an understanding of this particle source will contribute to our understanding of the interaction between the trapped radiation and the rings and moons.

In another project we are cooperating with a graduate student from the Institute of Geophysics of the National University of Mexico in Ensenada, and collaborating with UCLA to investigate particle fluxes near the magnetopauses of Jupiter and Saturn at times selected as Flux Transfer Event (FTE) candidates. In addition to the motivation the UCLA group has to pin down the reconnection process, we would like to gain a better understanding of the escape of energetic electrons from the Jovian magnetosphere, which is a problem of long-standing interest. [See, e.g.: Fillius, W., W.-H. Ip, and P. Knickerbocker, "Interplanetary Electrons: What is the Strength of the Jupiter Source?" Proceedings of the 15th International Cosmic Ray Conference, Plovdiv, Bulgaria, 1977, Vol. 11, pp 334-339.]

Leads for Future Research

Combination of the random-impact model of particle loss with the diffusion analysis results in constraints on the amount of absorbing material and the absorber size distribution. We wrote a preliminary paper on this result, but did not publish it pending results of a more sophisticated analysis, as described above under "Progress." This analysis is ready to complete, and our results must then be published.

The spatial profile of the absorbing ring material is also immersed in the trapped radiation data as a deconvolution of the absorption profile with the magnetic field line spread function. Although we have line spread functions, we have found that the location of the absorbers can be inferred accurately only by doing a numerical integration of the particle diffusion equation, using a model for the particle latitude distribution. Such models have been unsatisfactory to date, but we believe that the angular distribution data named above will give us enough of a handle to make this procedure

tractable. The result matters, because neither the visible ring of micron-sized particles nor the shepherding moons appear to be responsible for all of the trapped radiation absorption. Thus we are inferring the location of an invisible component, which is probably also the parent material, or "mooms," for the dust ring.

We would also like to solve the problem encountered with the Jovian electrons, where there are synchrotron losses in addition to the ring absorption. This will require a numerical approach, which we are developing anyway. Our hypothesis, which we hope to substantiate, is that this accounts for an apparent difference between the amount of ring material encountered by the electrons and by the protons.

Finally, we note that the principles and techniques developed here for the Jovian ring are applicable to Saturn and Uranus as well. Going further, Hannes Alfven explicitly cites the spatial profile of Saturn's A, B, and C rings as evidence that these sweeping mechanisms took place four billion years ago during the formation of the solar system. The work is difficult, but worthwhile.

TRAPPED RADIATION ABSORPTION AT THE RING OF JUPITER

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Trapped Particle Absorption at the Ring of Jupiter

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ABSTRACT

Pioneer 11 instruments recorded absorption dips in trapped radiation intensities when that spacecraft flew inside the ring of Jupiter in December, 1974. The correct explanation for these features was suggested, but regarded as unlikely until Voyager 1 and 2 pictures showed the ring and two small satellites. We have plotted the Pioneer 11 data and the position of the ring in magnetic coordinates. Magnetic field models using Pioneer 11 data must be used to produce a satisfactory match. In magnetic coordinates the ring is spread out over 0.25 R_J, but the absorption dip is surprisingly narrow. The minimum L shell reached by Pioneer 11 was inside most, but not all, of the ring material. Using a model for the sweeping rates of ~0.8 Mev and ~107 Mev protons, we infer a sweeping area of ~5 x 10^{13} cm^2 for material bigger than cobblestones (ie: thickness >7 gm cm^{-2}). The electron channels give different results, apparently because our model does not include synchrotron radiation losses. The satellites 1979-J2 and -J3 were not accounted for in the sweeping model. They may do a substantial amount of the sweeping, but more modeling is needed to evaluate their effect.

I. HISTORY

The first detection of the ring of Jupiter was actually made in 1974 by several of the trapped particle sensors aboard Pioneer 11. This spacecraft approached Jupiter to a distance of only 1.595 R_J from the planet's center and crossed the ring plane at 1.635 R_J. Thus its trajectory passed inside the brightest portion of the ring between 1.72 and 1.81 R_J, and penetrated the faint portion which extends inward to Jupiter's surface [Jewitt and Danielson, 1980]. Evidence for the ring occurred in profiles of the trapped radiation intensities measured by several charged particle detectors on board [Fillius et al, 1975; Van Allen et al, 1975; Simpson et al, 1975]. Figures 1(a) and (b) reproduce figures published by Fillius et al [1975] and Thomsen [1979] showing data from the University of California, San Diego (UCSD) and the University of Iowa experiments respectively. Other published data showing absorption effects are in Van Allen [1976] (Figures 21 and 23) and Simpson and McKibben [1976] (Figures 3 and 5). The sampling rate of the Goddard Space Flight Center experiment was apparently too low to resolve structure on this time scale.

Although this detection preceded the Voyager ring images of 1979, the method of observation was too indirect and the interpretation was too ambiguous to certify the discovery. Note in Figures 1(a and b) that most of the traces contain five relative maxima and four relative minima. The outer two minima, labeled N1 and N4 in Figure 1(a), were readily identified with the well-known satellite Amalthea. Such dips result from absorption of the trapped radiation by the satellites. They had been observed before at the orbits of Europa and Io [See, e.g., Mogro-Campero, 1976; Thomsen, 1979] and such effects were even predicted before the Pioneer encounters [Mead and Hess, 1973]. Minima N2 and N3 occur in a position not associated with any previously known orbital

object. We know now that they are caused by the previously undiscovered ring and/or the satellites 1979-J1 and 1979-J3. However, in 1974 this did not seem so obvious. The complexity of Jupiter's magnetic field raised the possibility that particle drift shells might be so rippled that the spacecraft trajectory penetrated them twice [Fillius et al, 1975; Acuna and Ness, 1976a]. Furthermore, at these low altitudes the detector look directions began to include the planetary loss cone, so that absorption by the planetary atmosphere needed to be considered [Fillius et al, 1975; Acuna and Ness, 1976a; Roederer et al, 1977]. The first authors to venture into print with the correct hypothesis were Acuna and Ness [1976a]. Fillius [1976] welcomed their suggestion. Undoubtedly we would have embraced the correct explanation earlier and more vigorously if we had had any idea of the difficulty of making ground-based observations so close to such a bright object as Jupiter. The alternatives suggested before Voyager still exist as factors to be accounted for in detailed interpretations of the ring absorption effects. However, it is now clear that the major feature at N2 and N3 is caused by absorption by orbiting material.

It is fortunate that the Pioneer and Voyager observations were made by different techniques. Intercomparison of results from two techniques should yield more information than from either alone. In this paper we will examine two aspects of the trapped radiation data in an attempt to contribute to a better understanding of the ring: first is the use of magnetic coordinates to obtain a profile of the absorbing material; and second is the formulation and calculation of absorption rates to obtain inferences concerning the amount of absorbing material. In Section II, we introduce magnetic coordinates and display our data in two magnetic coordinate systems. In Section III we present a mathematical model for analyzing particle absorption by the ring. We will not evaluate the effects of the companion

satellites 1979-J1 and -J3 at this time. Thus our model is not complete; however, it may be extended in a straightforward way. The present model will illuminate some of the key features of the interaction.

II. MAGNETIC COORDINATES

Because the trajectories of trapped particles are guided by the magnetic field, magnetic coordinates must be used to relate the position of the ring to that of the absorption features. McIlwain [1961] formulated the (B,L) coordinate system that is in nearly universal use today. For a given position, the integral adiabatic invariant

$$I = \oint \sqrt{1 - B/B_m}\ ds \qquad (1)$$

is calculated numerically along a line of force between mirror points, using a spherical harmonic representation of the field. (There are more than a dozen magnetic field models which have been published for Jupiter [Smith et al, 1976; Smith and Gulkis, 1979; Acuna and Ness, 1976b]. The L coordinate is then derived from an empirical function,

$$(L^3 B_m/M) = f(I^3 B_m/M) \qquad (2)$$

where B is the magnetic field magnitude at a test point, B_m is the magnetic field magnitude at the particle mirror point, and M is the strength of the dipole term in the field expansion. Being based on the adiabatic invariants of particle motion, the (B,L) coordinates are a distortion-free system for locating trapped particles. To visualize (B,L) space it is intuitively helpful to know that, thanks to McIlwain's selection of $f(I^3 B_m/M)$, L is nearly constant along the drift shell traversed by a given particle. Invariant (R,λ) coordinates are often based on the (B,L) system by using

relationships for a dipole magnetic field,

$$R = L \cos^2\lambda \qquad (3)$$

$$B = (M/L^3) \sqrt{4 - 3 R/L} \qquad (4)$$

Invariant (R,λ) coordinates can be plotted like ordinary polar coordinates, and particle drift shells will look like families of undistorted dipole field lines. The difference between invariant, or magnetic, (R,λ) coordinates and ordinary, or graphic, (R,λ) coordinates is that, in the latter, space is undistorted and field lines are irregular, whereas, in the former, space is distorted in such a way that the field lines are regular, but other surfaces appear distorted.

This difference is illustrated in Figures 2(a) and 2(b), which show the Pioneer 11 trajectory past Jupiter in a meridian plane projection. If field lines were drawn in Figure 2(a), they would appear irregular and they would not be degenerate in longitude. In 2(b) field lines would be smooth and degenerate, but the surface of Jupiter and the orbits of the satellites and ring are not. (The surface of Jupiter was calculated only up to 60^o latitude, because the integration path for equation (1) becomes prohibitively long for field lines near the pole.) The field lines are easier to locate in a coordinate system where they are straight, as with (B,L) coordinates. Figure 3 (top) shows the transformation of 2(b) into the (B,L) system by equations 3 and 4. The reader can verify that the spacecraft was on L shells occupied by ring material from about 0515 to 0545 UT (spacecraft time). The peak at 0540 (see Figure 1) coincides with the magnetic equator crossing, where trapped radiation intensities are usually highest.

In Figures 2(b) and 3 it can be seen that the ring occupies L shells that cross the equator over a range, ΔL, of $0.25\ R_J$. The ring material is not uniformly distributed over

this range. Figure 3 (bottom) shows the L distribution of material for a model ring that is infinitessimal in radial width, uniformly distributed in longitude, and located at 1.76 R_J. This part of the figure is a histogram made by calculating the L values for 500 points evenly spaced around the entire ring orbit, and then sorting these L values into bins of width 0.005 R_J. Jupiter's equator and the satellites JV and 1979-J2 are also shown in the same way.

Figure 3 reveals something about the trajectory that was previously obscure: the minimum L shell reached by Pioneer 11 was not lower than the minimum L shell occupied by the ring. This means that the trapped particles sampled by Pioneer 11 at this point had not passed clear of all the absorbing material. Specifically, with magnetic field model 04 used in Figure 3, this point is inside 78% of the ring material. With magnetic field model P11(3,2)A, this point is inside 85% of the ring material.

Figures 4 and 5 show data from Figure 1 plotted against the magnetic coordinate L. The vertical displacement between the inbound and outbound counting rates is due to the difference in latitude between inbound and outbound crossings of the same L shell. The higher intensities belong to the outbound leg, where the spacecraft was closer to the magnetic equator. The distinction between Figures 4 and 5 is that we used different spherical harmonic expansions to represent the magnetic field in the computation of L: model 04 [Acuna and Ness, 1976b] for Figure 4; and the internal terms of model P11(3,2)A [Smith and Gulkis, 1979] for Figure 5. When we derive the magnetic coordinates from other field models, we find that offset, tilted dipole models and models based only upon Pioneer 10 data show clear horizontal misalignment between inbound and outbound features. Since the L parameter organizes the trapped particle motion, we demand that corresponding features appear on the same L shell. Thus

horizontal misalignment is unacceptable. The only satisfactory models are spherical harmonic expansions based upon Pioneer 11 data or Pioneer 10 and 11 data combined. This is not surprising, since the importance of the higher harmonics increases as one approaches the planet, and Pioneer 10 came no closer than 2.85 R_J.

The L distribution of absorbing material for the model ring is shown at the bottom of each figure. Actually, since the real ring is not infinitessimal, the real L distribution is a convolution of the radial distribution of ring material with the L spread function shown. Considering the smearing introduced by the convolution and the magnetic spreading, the absorption dip is rather narrow and the location is rather precise. Although Jewitt and Danielson [1980] list the bright ring as extending from 1.72 to 1.81 R_J, the particle absorption feature appears to be narrow enough to imply a more limited distribution of absorbing material. The only feature listed within the ring by Jewitt and Danielson is an annulus of width 0.01 R_J, 10% brighter than the adjacent material, located at 1.79 R_J. We chose the position of our model ring, 1.76 R_J, so that the dips in the particle intensities correspond with the outboard spike in the ring distribution, which contains ~50% of the ring material (46% for model 04; 51% for P11(3,2)A). One can see by inspection that the absorber could not be placed any closer to the planet, but a slightly larger radius might be tolerable. Perhaps the radiation is absorbed in the bright annulus. This position could be refined by integrating the diffusion equation and trying to match the observed profile.

To summarize, magnetic coordinates must be used to relate the ring to the trapped particle features. More work in this area, bolstered by a better understanding of the trapped particle absorption dynamics, should be fruitful. This would include latitude effects, different magnetic field

models, loss cone effects, and the distribution of absorbers in the ring.

III. CROSS-SECTIONAL AREA OF THE RING DEDUCED FROM TRAPPED RADIATION ABSORPTION

Trapped radiation absorption by the satellites of Jupiter has been treated in other papers and reviewed by Mogro-Campero [1976] and Thomsen [1979]. Absorption by planetary rings has been discussed by Thomsen and Van Allen [1979], Ip [1979], and Fillius et al [1980a]. In principle, one can deduce the nature and amount of the ring material from the trapped particle observations. All of these authors formulate similar expressions for the loss rate in terms of the amount of ring material. However, they use different methods to model the data. Ip and Fillius et al take the naive attack of integrating the loss rate directly for the estimated length of time the particles spend in the sweeping region. The result is the fraction lost across the hazard, which can be compared with an estimate based on the data. Thomsen and Van Allen use the more formal approach of substituting the loss rate into the radial diffusion equation and varying the parameters to obtain a solution which matches the data. We will use the naive approach below, as it is considerably simpler, and adequate for a survey of the problem.

The loss rate, $-dn/dt$, is proportional to trapped particle density n times some probability p of absorption per unit of time t:

$$dn/dt = -np \qquad (5)$$

This is the loss rate during T_R, the residence time of the particles in the region swept by the ring or moon. Integrating (5) from $t=0$ to $t=T_R$ gives an expression for the

fraction that survives, n/n_o:

$$\ln(n/n_o) = -pT_R \tag{6}$$

To estimate p, picture a ring as an annulus of width S and circumference $2\pi R$ containing a randomly spaced collection of small objects, the sum of whose cross-sectional areas is called A. As the data show that the objects are very sparse, we can assume they do not overlap, and the opacity measured perpendicular to the ring plane is given simply by $\eta = A/(2\pi RS)$, with $\eta << 1$. Every time a trapped particle crosses the equator within the annulus S, its chance of hitting one of the objects is $A/(2\pi RS \cos\alpha)$ where α is the angle between the particle's trajectory and a normal to the ring plane.

When viewed in a magnetic coordinate system, the ring annulus is neither circular nor centered on Jupiter, and consequently the distribution of ring material, $\Delta A/\Delta L$, is unevenly spread over a range $W \approx 0.25\ R_J$ as shown in Figures 2-5. Rather than model the uneven distribution of $\Delta A/\Delta L$, which would require numerical methods, we will use the average value of A/W. Particles that are within W may or may not be within S, depending upon their longitudes. We will let p be a longitudinal average, because the trapped particles execute many longitudinal drift cycles during their residence time in W. With these simplifications the probability of absorption per unit time is given by

$$p = p_c = (2/T_b)\ (A/(2\pi RW \cos\alpha)) \tag{7}$$

where T_b is the particle's bounce period. We have assumed that a single hit annihilates a particle. This assumption is true if the orbiting object is thicker than the range of the energetic particle. We will consider this case only.

The substitution of (7) into (6) gives an expression for A, the absorbing cross-section of the ring material.

$$A = -\pi R\ T_b \cos\alpha \ln(n/n_o)\ (W/T_R) \tag{8}$$

This expression contains several known and measurable quantities, plus the ratio W/T_R, the width of the hazard divided by the time the particles spend in it. We must estimate this ratio separately.

To satisfy this need, Ip [1979] referred to published values of the diffusion coefficient [Mogro-Campero and Fillius, 1976; Mogro-Campero, 1976] to derive a diffusion time. While this approach is reasonable, we note that the referenced diffusion coefficients were obtained by modeling the trapped radiation losses at Europa, Io, and Amalthea, using expressions similar to (8). These expressions were solvable for the particle diffusion coefficient because the dimensions of the satellites are known. We can make our discussion more consistent and self-contained by using such an expression to obtain the analogous ratio directly at Amalthea, and extrapolating it the small distance inward to the ring.

The probability of absorption must be reconsidered for Amalthea, because the longitudinal distribution of absorbing material is not random; the particle and satellite can meet only when their relative longitudinal motions bring them to the same meridian. As argued by Mogro-Campero and Fillius [1976], the problem can still be formulated probabilistically if the width, W, of the region where the particle might encounter the satellite is much greater than the effective diameter, d, of the satellite. Then the probability of absorption during each orbit is just d/W, and the probability per unit time is

$$p = p_m = d/(PW) \tag{9}$$

where P is the period of the satellite measured in the particle drift frame. (The relative drift velocity of some particles is high enough to carry them past Amalthea during one half of their latitudinal bounce period, and for these particles the absorption probability is reduced accordingly. This process is often called "leapfrogging." However, the particles detected by Pioneer 11 cannot evade absorption this way, and so we will ignore this complication.)

Note the difference in the expressions for p_m and p_c. The parameter that characterizes the size of the absorber has the dimension of length for a satellite, but the dimension of area -- or length squared -- for a ring of cobblestone-sized objects. This difference has been overlooked by some authors who treated both cases as proportional to the area of the absorber. The distinguishing feature between these two cases, and thus between rings and satellites for our purposes, is that the trapped particles cannot leapfrog a satellite, but they can leapfrog the component objects of a ring.

When equation (9) is substituted into (6), we get an expression which we can solve for the ratio W/T_R at Amalthea.

$$(W/T_R)_{Am} = - \ d \ / \ (P \ \ln(n/n_o)_{Am}) \tag{10}$$

Now by combining equations 8 and 10 we can express the absorbing area of the ring material in terms of known and measurable quantities multiplied by a dimensionless factor, $\gamma = (W/T_R)_R) \ / \ (W/T_R)_{Am}$, which contains the extrapolation from Amalthea to the ring.

$$A = \gamma \ (\pi R T_b \cos \alpha)_R \ (d/P)_{Am} \ (\ln(n/n_o)_R \ / \ \ln(n/n_o)_{Am}) \tag{11}$$

The subscripts R and Am denote that quantities are to be evaluated at the ring ($R = 1.76 \ R_J$) and at Amal a ($R = 2.54$

R_J) respectively. Because Amalthea is rather close to the ring we believe γ will be of the order of unity; however, we can construct arguments to estimate its value.

One approach is to identify W/T_R with a bulk flow velocity V, given by $J = nV$, where J is the diffusive flow. To evaluate J we use Fick's Law [Crank, 1975]: $J = -D \text{ grad } n$, where D is the diffusion coefficient; and so we get $W/T_R = -D \text{ grad}(\ln(n))$. It is widely accepted that the diffusion coefficient varies as the third or fourth power of the distance from Jupiter [Mogro-Campero, 1976; Thomsen et al, 1977]. We don't really know the variation of grad(ln(n)), but we can try different functional forms and compare the results. Thus, assuming that the density has an exponential dependence with distance from Jupiter, $n \propto (\exp(L/L_o) - \exp(1/L_o))$, and using the third power for the diffusion coefficient, $\gamma = 1/3$. Alternatively, assuming that the density has a power law dependence, $n \propto (L-1)^m$, and the result is $\gamma = 2/3$.

The bulk flow velocity can be misleading when dealing with diffusion, because the net distance traveled by a particle does not increase linearly with time, as it would for convective flow. We can also estimate γ without using this concept. If an ensemble of particles, having infinitessimal width at time $t = 0$, propagates diffusively, the width of the ensemble increases with time so that, at time t, $\langle \Delta R^2 \rangle = 4Dt$, where $\langle \Delta R^2 \rangle$ is the variance of the displacement of the particles [Mogro-Campero and Fillius, 1976; Thomsen, 1979]. In our problem t is the residence time, T_R, in W, and $\sqrt{\langle \Delta R^2 \rangle}$ is W/2. Then W/T_R is proportional to D/W. Since W is about the same for both Amalthea and the ring (See Figures 3-5), γ becomes just the ratio of diffusion coefficients. Using as before a power law with exponent equal to 3, $\gamma = 1/3$.

As our estimates for γ vary from 1/3 to 2/3, we take note of the uncertainty and adopt a compromise value of 1/2.

The rest of the quantities needed to evaluate equation (11) are listed in Table I for the particles in four different data channels. For α (and T_b and P, which are mild functions of α [Schulz and Lanzerotti, 1974]) we used values appropriate to particles which mirror at the magnetic latitude of the spacecraft. Quantities which depend upon the particle energy were evaluated at an average energy obtained by integrating a model spectrum over the detector response. For the proton channels $\bar{E}$ = 0.8 and 107 Mev, corresponding to an E^{-4} spectrum; and for electrons $\bar{E} = 2\ E_{th} + 100\ L^{-3/2}$ where E_{th} is the threshold energy for the channel and the model is from McIlwain and Fillius [1975]. We compromised on quantities which differed between the inbound and the outbound crossings. The fraction of particles to survive each hazard is a judgment based upon Figures 1, 4, and 5. This involves some imagination. However, since the result depends upon the ratio of values at the ring and Amalthea, our errors of judgment should tend to cancel, if they are consistent. The comparison is also easier because the dips in the profiles are similar in magnitude and, furthermore, $\ln(n/n_o)$ is a slowly varying function. Thomsen, Goertz, and Van Allen [1977] and Thomsen and Van Allen [1979] developed a curve-matching procedure based upon an integration of the diffusion equation, and their procedure should be less subjective. However, there are shortcomings of greater significance in the model we have used for the particle loss rates. We will defer a discussion of these defects until after we have examined our results.

The absorbing cross-section of ring material deduced from the above model is listed in Table II for each of five energy channels. We assumed that the observed absorption was accomplished by only 80% of the ring material, as we found in Section II. For the 80 Mev proton channel the present result differs from that presented at the "Satellites of Jupiter" meeting [Fillius et al, 1980b] and that published by Ip

[1979], mostly because the previous calculations were carried out for $\alpha = 0^{o}$, and Ip used a shorter diffusion time obtained from the literature. This is the first time results have been published for the other channels. Obviously so much disagreement between the electron and proton channels is unsatisfactory. However, it is remarkable that the two proton channels produce the same result, because, as seen in Figure 1, there is a large contrast in their absorption profiles. Table I shows that the difference in their absorption at Amalthea is primarily due to an order of magnitude difference in their drift orbital periods with respect to that satellite. The difference in their absorption at the ring is similarly explicable by an order of magnitude difference in their bounce times. It is encouraging that these factors seem to operate the way they are modeled. For the electron channels the absorption profiles and the model parameters are all similar, and so the results are necessarily alike, irregardless of the model.

We have not allowed for the effects of synchrotron radiation on the energetic electrons, although the ring is in the heart of the radio emission region. We estimate that the electrons take many weeks to diffuse across the ring. Their synchrotron lifetime in this region is about a month, and so this omission is probably important. To include this factor properly we would have to integrate the diffusive transport equation numerically with the synchrotron, and possibly other loss terms [Fillius et al, 1976; Baker and Goertz, 1976]. Instead, we will merely name two ways in which the synchrotron radiation can be expected to alter our model. One effect will be to reduce the mean energy in each channel, because the higher energy particles radiate faster, softening the spectrum. The other effect will be to reduce the depth of the absorption features, because the radiative loss rate, being proportional to the particle density, will be higher on the shoulders than in the bottom of the dips. This effect will

lead to an underestimate of the ring cross-section, and thus it operates in the right direction to account for the difference between the proton and electron results.

If synchrotron radiation explains away the electron results, and if the agreement between proton channels means that our absorption model is valid, we can infer something about the size of the absorbers. Since our model is based upon one-hit annihilation of the trapped particles, it implies that the size of the absorbing objects exceeds the range of an 80 Mev proton, ~7 gm cm^{-2}. The absorbers would then have to be bigger than small cobblestones or snowballs ($r > 7$ cm).

Although it is an improvement on previous estimates, the present calculation is still deficient in several other important respects. For instance, we have not included latitude effects. If a trapped particle mirrors at a magnetic latitude lower than that of the absorber, it escapes absorption, and an appropriate factor should be included. Further, we have considered only the case in which a ring object annihilates the trapped particle that hits it. For objects smaller than the range of the charged particle, several hits might be needed; and for very small objects, a continuous degradation model would be more appropriate. For this case, the absorption rate is proportional to the mass of the ring, or the cube of the linear dimension of the absorbers. Our treatment also does not cover the transition from cobblestone-sized objects to satellites. For such intermediate objects one must introduce skipping factors to represent the possibility that the particle will get by the object when their longitudes cross. Finally, if material of different sizes contributes to the absorption, it will be necessary to use a combined absorption model. The present model is a foundation upon which these factors may be added, but it will be left to a future paper to carry out all of these improvements.

IV. DISCUSSION

The material in orbit is more varied than we have so far pretended. The Voyager spacecraft has also identified two satellites in or near the ring. The first, 1979-J1, is at about 1.81 R_J as deduced from the measured period of 7h 09m $\pm$ 01m. Its diameter is estimated at 25 km [Jewitt et al, 1979]. The second satellite, 1979-J3, is at 1.79 R_J based on the measured period of 7h 04m 30s $\pm$ 03s, and its diameter is estimated as 40 km by its discoverer, S. Synnott [I. A. U. Circular No. 3507, Sept. 1980]. The tally may or may not be complete, although it seems likely that the largest have been discovered, and any remaining objects would be pushing the resolution limits of the Voyager imaging system.

These objects should do an appreciable amount of sweeping. Their combined cross-sectional area is 1.75×10^{13} cm^2, which is smaller than, but comparable to the needed sweeping area we deduced in Section III for the ring. Alternatively, treating them as satellites and applying equation 10, we would expect between 1/4 and 1/2 of the absorption observed. Unfortunately, it is too simplistic to apply either of the above formulations to them, because these objects are in that intermediate size range where skipping is a possibility, and neither approach is valid. We expect that both approaches we have used will give overestimates of the loss rate in this size range. Skipping probabilities can be worked out, but we must leave that to a future paper.

The visual ring detected by Voyager falls on the other end of the size scale. As deduced from the forward/backscattering ratio, this ring is composed of grains only a few microns in size [Owen et al, 1979]. These grains cannot produce the one-hit annihilation that our data seem to

prefer, and, furthermore, there is not enough mass in these micron-sized grains to produce the observed absorption through multiple hits [Burns et al, 1980]. The position of the visual ring given by Jewitt and Danielson [1980] fits our absorption profiles much better than that given in the preliminary paper of Owen et al [1979], but as described in Section II, the absorption seems to be restricted to a portion of the visual ring, possibly the bright annulus. Thus it appears that the visual ring and the absorption ring are different systems, although their spatial coincidence indicates that they must be closely related.

Burns et al proposed that the micron-sized objects are the short-lived offspring of larger bodies, which they dubbed "mooms," orbiting in their midst. This is an appealing suggestion, because these bodies would presumably be bigger than cobblestones, and so they would produce one-hit annihilation. The mooms could then be the absorption ring. However, a difficulty arises with the cross-sectional area. Burns et al argued that the cross-sectional area of the mooms should be about equal to that of the visual ring; but our revised value of $\sim 5 \times 10^{13}$ cm^2 is substantially smaller than the $\sim 1 \times 10^{15}$ cm^2 in the visual ring [Jewitt and Danielson, 1980]. We do not know whether these numbers can be reconciled.

Besides the above, the size spectrum of the material in this orbit is unknown. With ten orders of magnitude between the extremes identified visually, the trapped radiation interaction spans three regimes. In the first regime, for small objects, the loss rate is proportional to the absorber mass. In the intermediate regime, the loss rate is proportional to absorber area; and in the last regime, the loss rate caused by each object is proportional to its effective diameter. The boundaries between these regimes are determined by the particle type and energy. Thus dealing with

an unknown size distribution of orbiting material requires extensive modeling. Nevertheless, it seems quite possible that a model ring (or a family of model rings) can be found that will satisfy all the constraints of the trapped radiation data. We believe that more progress will be made in this direction.

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Table I

		Protons		Electrons	
	E_{th} (Mev):	80	0.6	5	35
Amalthea	$\bar{E}$ (Mev):	107	0.8	35	95
L = 2.54	d (km):	396	281	280	296
$\alpha = 52^{\circ}$	P (hr):	4.5	53	55	13
	$\ln(n/n_o)$:	-1.6	-0.36	-0.36	-0.92
Ring	$\bar{E}$ (Mev):	107	0.8	53	113
L = 1.76	T_b (s):	2.9	31	1.3	1.3
$\alpha = 77^{\circ}$	$\ln(n/n_o)$:	-2.3	-0.69	-0.69	-0.92

Factors Affecting Particle Absorption at Amalthea and the Ring

The effective diameter given for Amalthea is the sum of the long dimension (270 km) plus two particle gyroradii.

Table II

The Absorbing Cross-Sectional Area of Ring Material

	Protons		Electrons		
E_{th} (Mev):	80	0.6	5	12	35
$\bar{E}$ (Mev):	107	0.8	53	67	113
Area (cm^2):	5.4×10^{13}	4.7×10^{13}	1.9×10^{12}	4.3×10^{12}	4.5×10^{12}

FIGURE CAPTIONS

Figure 1 -- Trapped radiation intensities measured by Pioneer 11 near periapsis, showing particle absorption at the position of Amalthea (N1 and N4) and the ring (N2 and N3).

(a) University of California, San Diego data.
(b) University of Iowa data.

Figure 2 -- Polar coordinate plot of the Pioneer 11 trajectory, showing the surface of Jupiter, the ring, Amalthea (JV), and newly discovered 1979-J2.

(a) Graphic coordinates.
(b) Magnetic coordinates.

Figure 3 -- Plot of the Pioneer 11 trajectory in B,L coordinates, with the surface of Jupiter, the ring, Amalthea, and 1979-J2. The value of the magnetic field is normalized to its equatorial value on each line of force. The absorbing material is distributed in L as shown in the bottom panel. (For Jupiter's surface the bottom panel only shows a ring on the equator.)

Figure 4 -- Pioneer 11 trapped radiation data plotted vs the magnetic coordinate L, computed using magnetic field model O4. Channels M1 and M3 exhibit a small amount of spin-aliased roll modulation, which coincides with and probably accounts for the dip at the position of the small satellite 1979-J2. The data plotted as dots were taken during occultation, and represent the highest resolution available during that interval.

Figure 5 -- Same as Figure 4 except that the magnetic field model was P11(3,2)A, internal terms.

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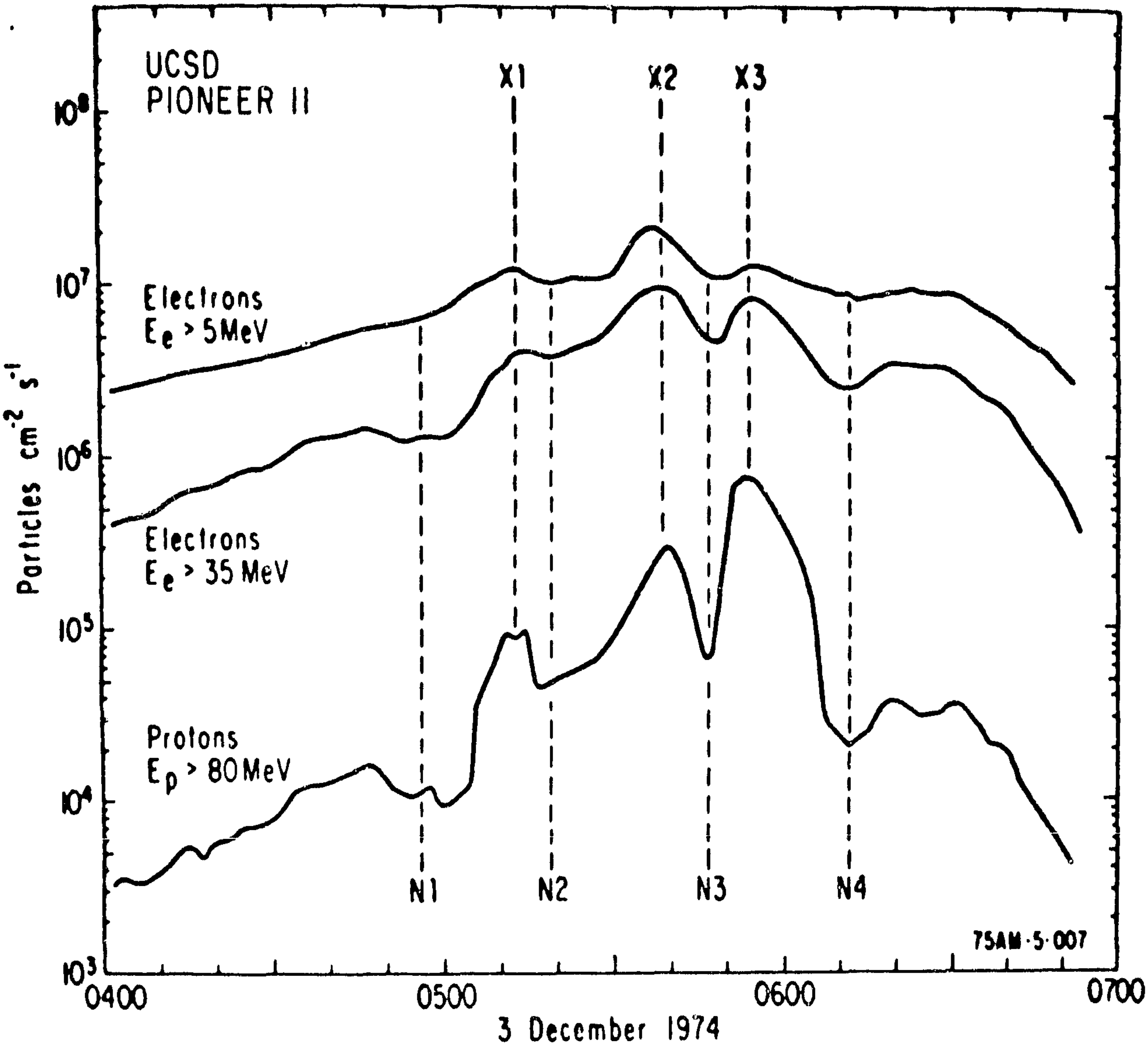
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PIONEER II
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X2
X3
Electrons
E_e > 5MeV
Electrons
E_e > 35 MeV
Protons
E_p > 80MeV
N1
N2
N3
N4
75AM-5-007
Particles cm^{-2} s^{-1}
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10^5
10^4
10^3
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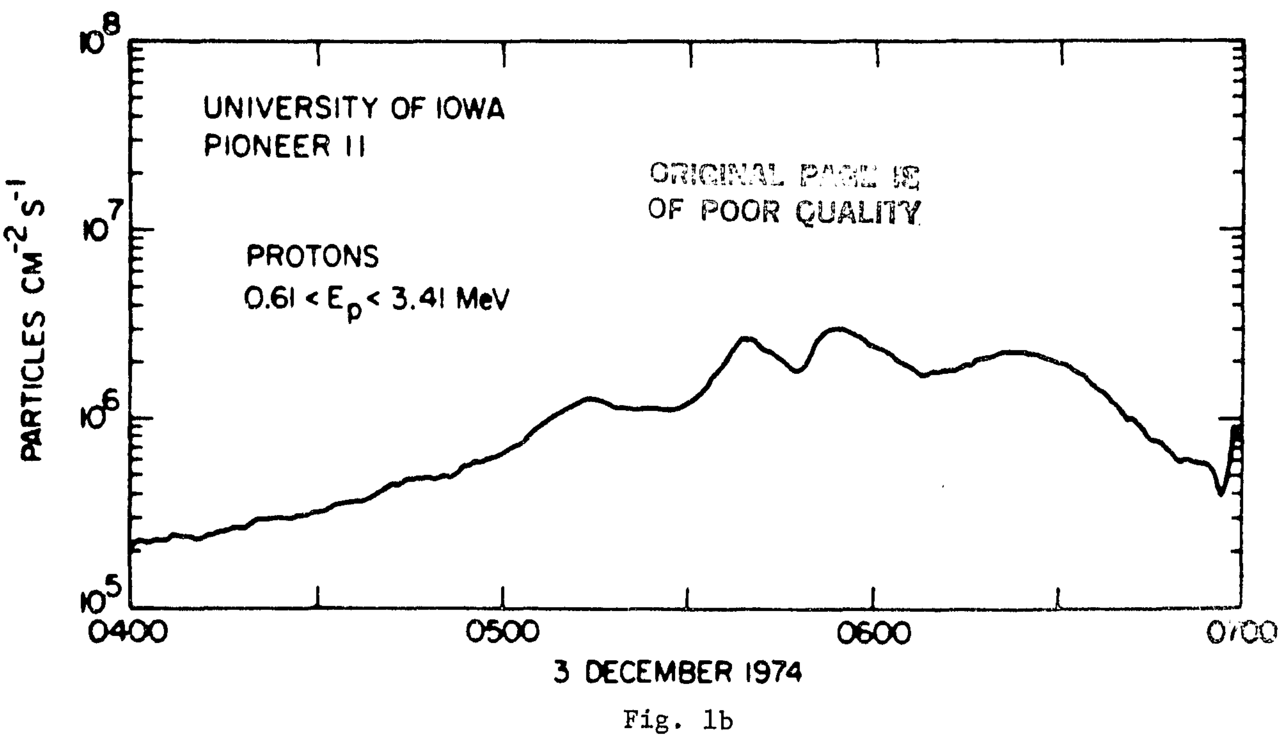
0500
0600
0700
3 December 1974


UNIVERSITY OF IOWA
PIONEER II
PROTONS
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10^6
10^5
0400
0500
0600
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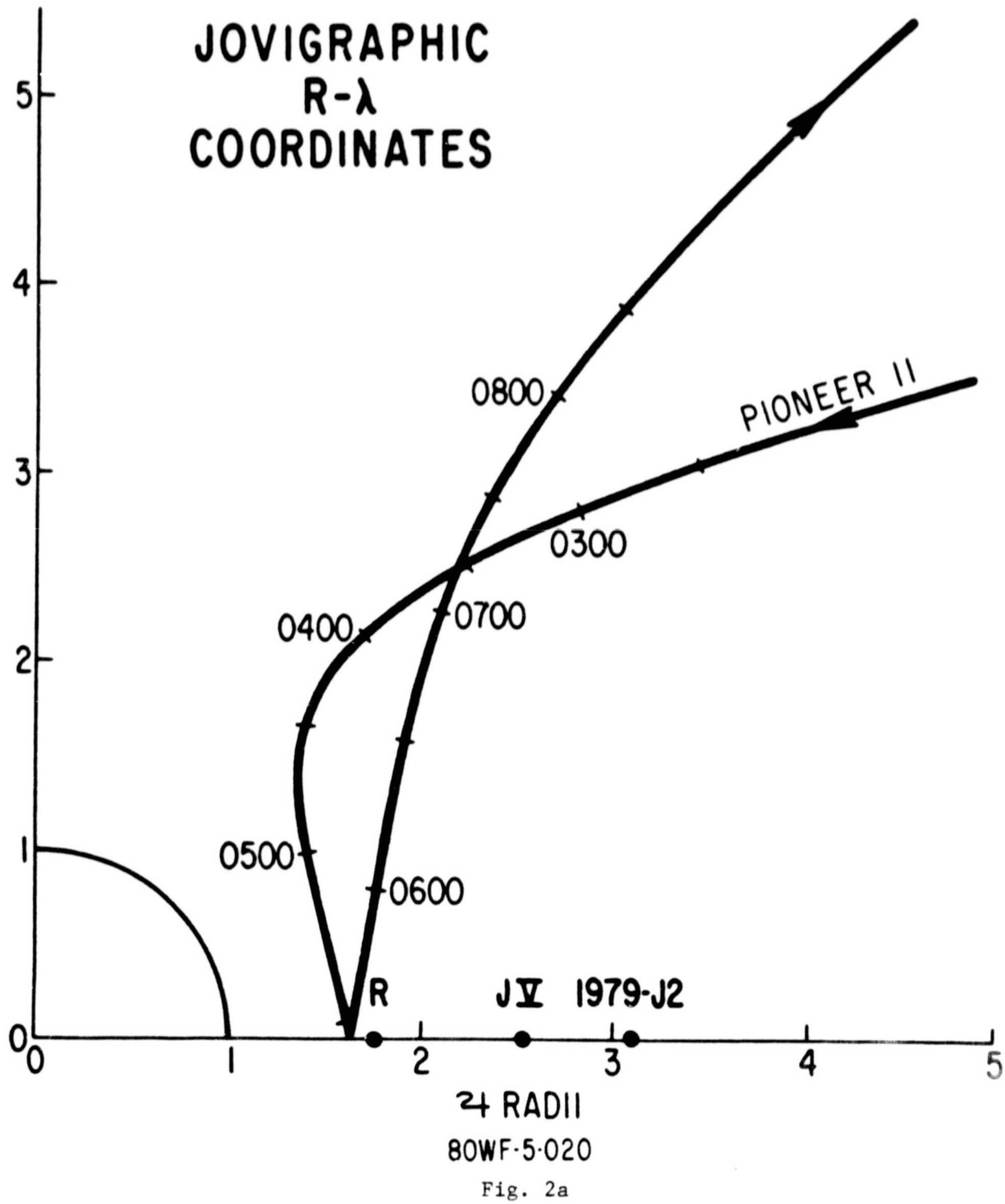
3 DECEMBER 1974

Fig. 1b


JOVIGRAPHIC
R-λ
COORDINATES
PIONEER 11
0800
0300
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JV
1979-J2
0
1
2
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4
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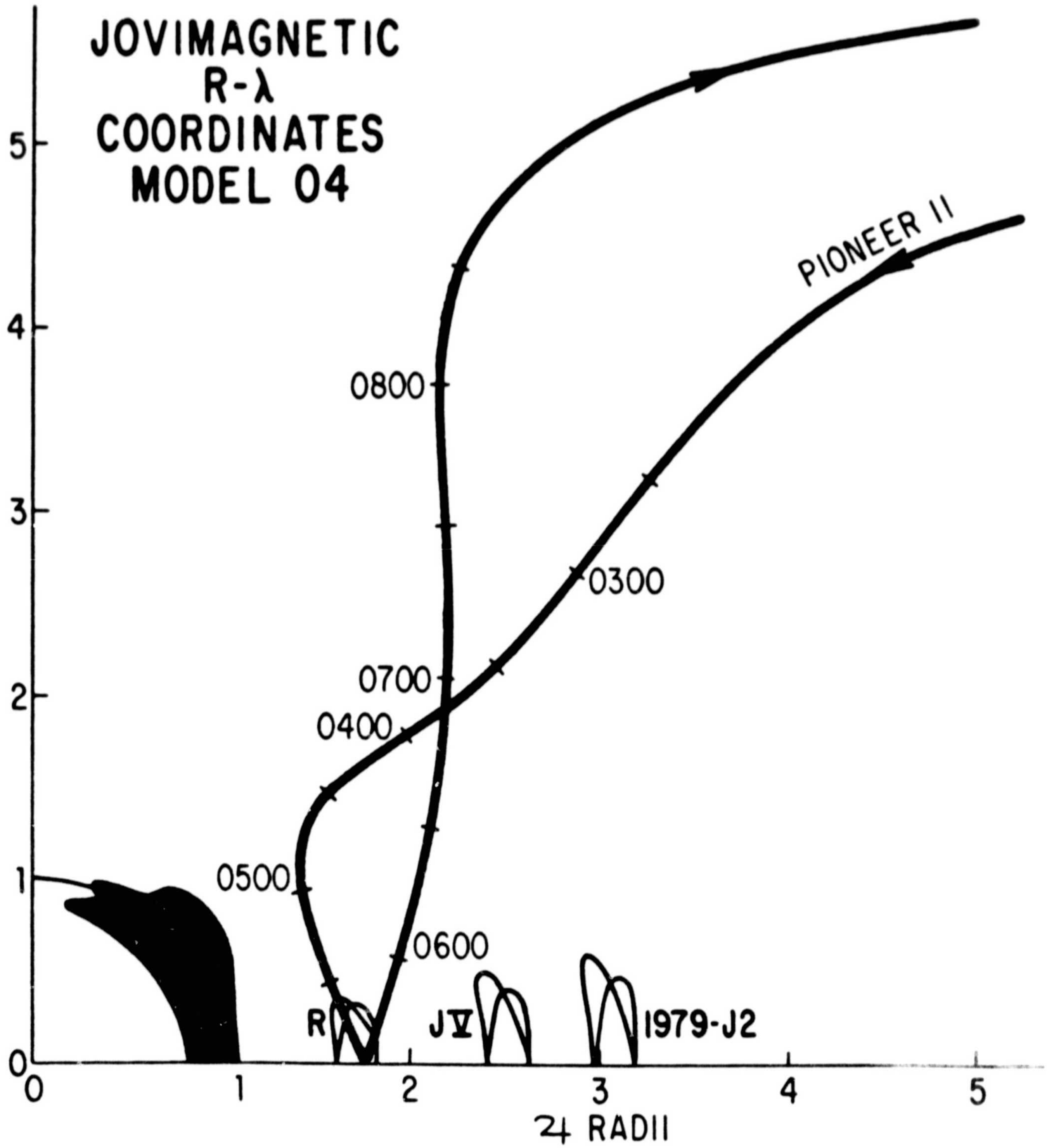
♃ RADII
80WF-5-020

Fig. 2a



80WF·5·011

Fig. 2b

MAGNETIC COORDINATES

MODEL 04

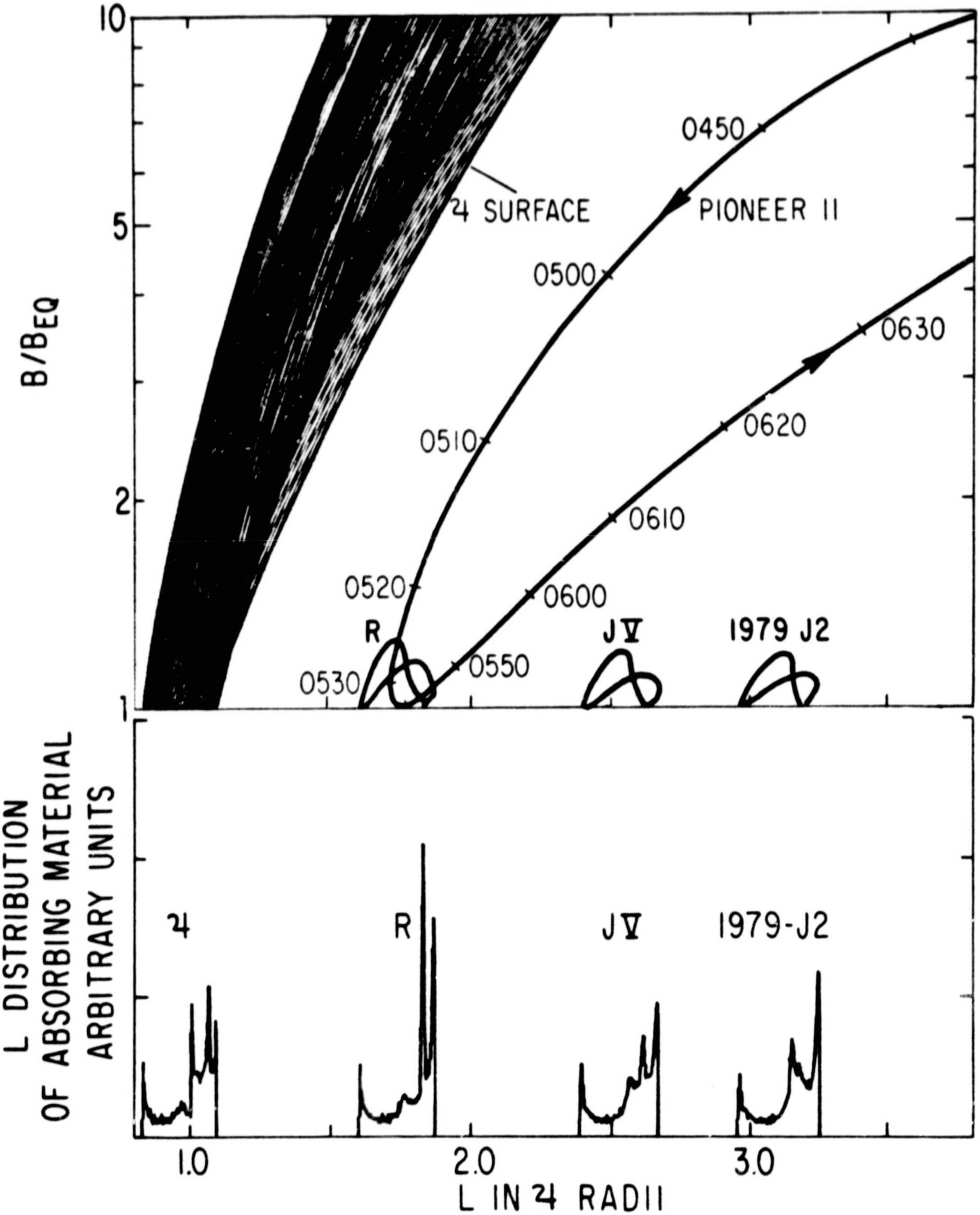


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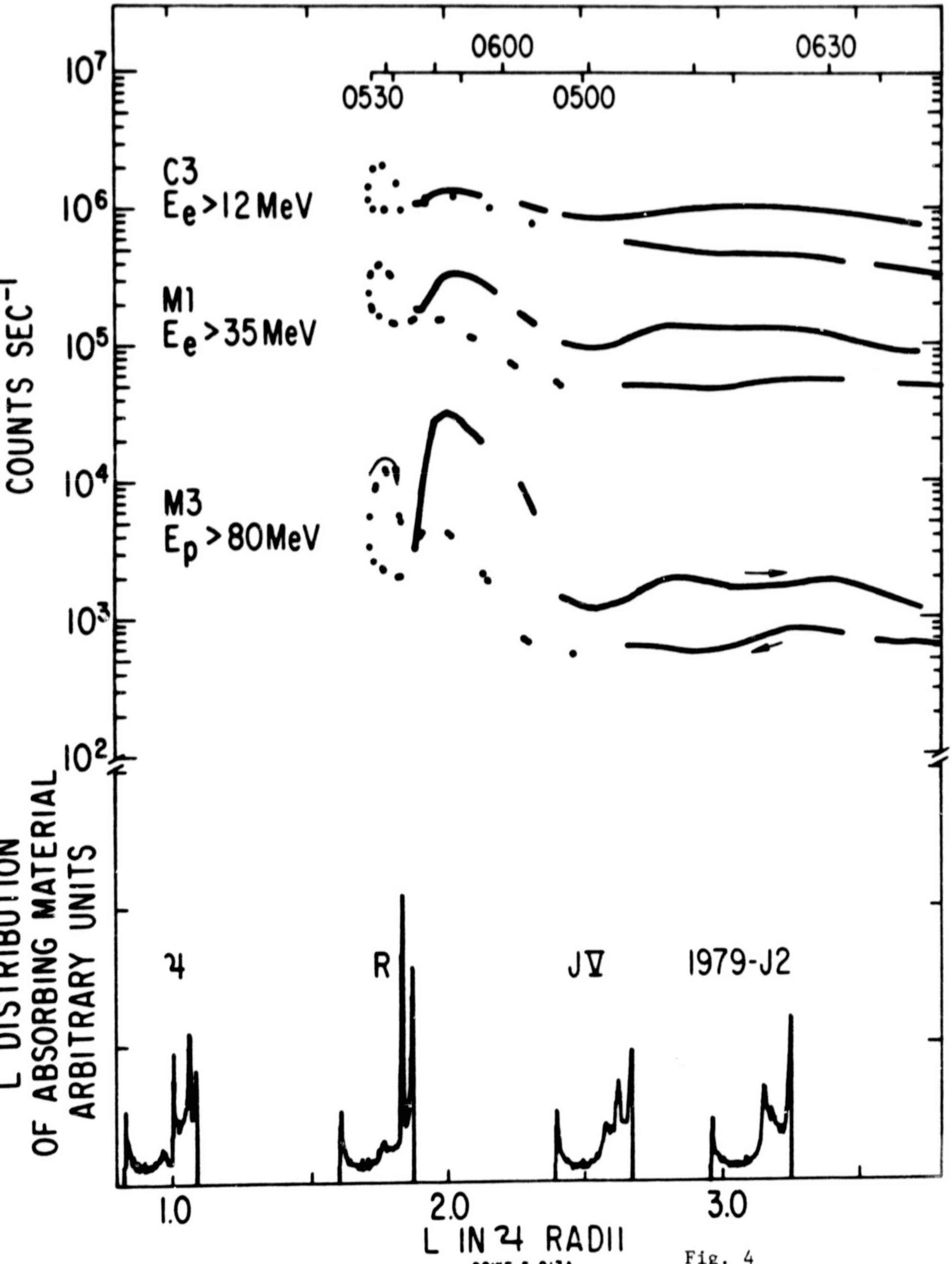
Fig. 3

TRAPPED RADIATION ABSORPTION BY RINGS & MOONS

MAGNETIC MODEL 04



BOWF 5 013A

Fig. 4

TRAPPED RADIATION ABSORPTION BY RINGS & MOONS

MAGNETIC MODEL PII(3,2)A
INTERNAL TERMS ONLY

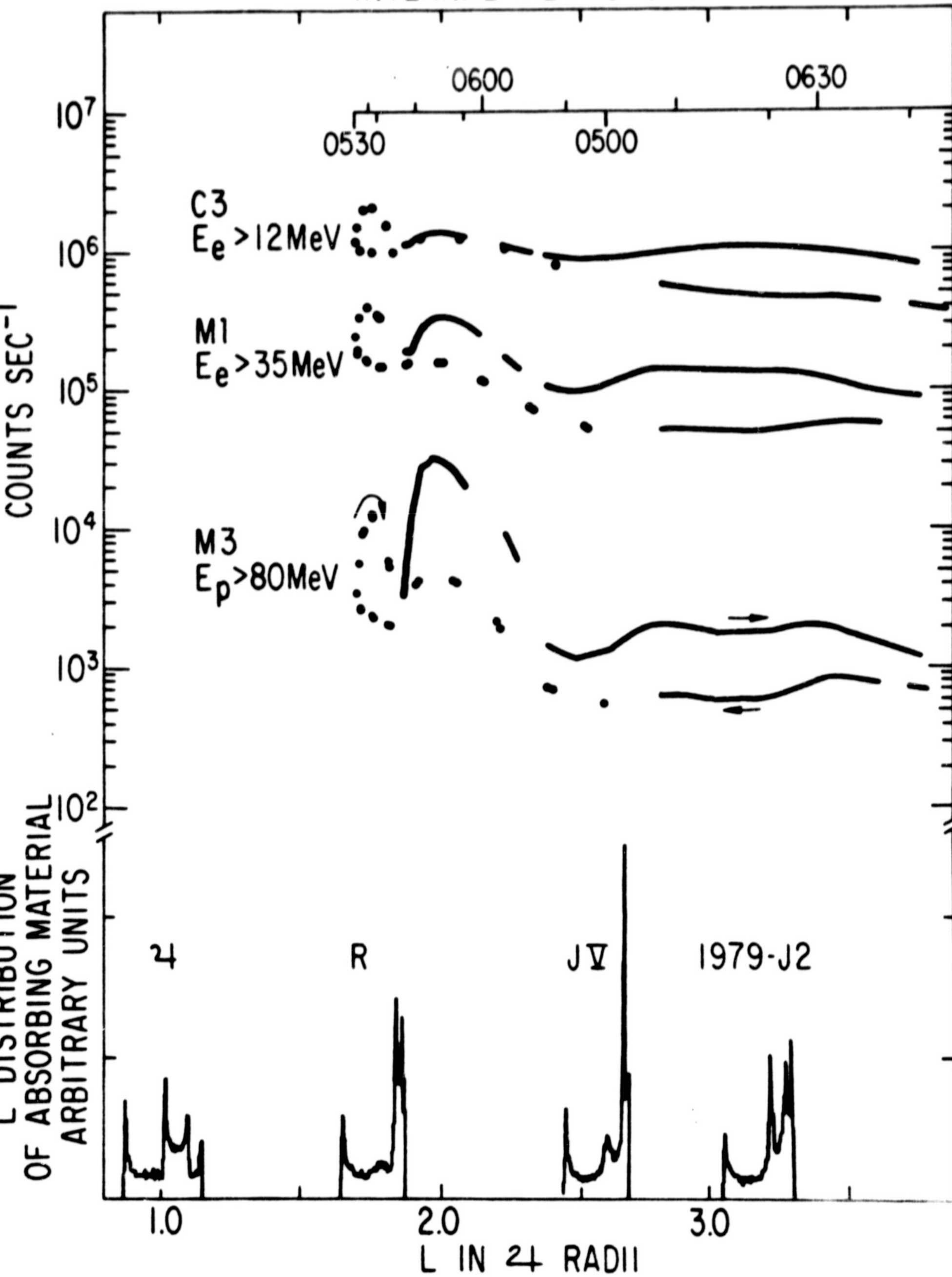


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Fig. 5